SHENANDOAH NATIONAL PARK

GEOLOGIC RESOURCE MANAGEMENT ISSUES

SCOPING SUMMARY

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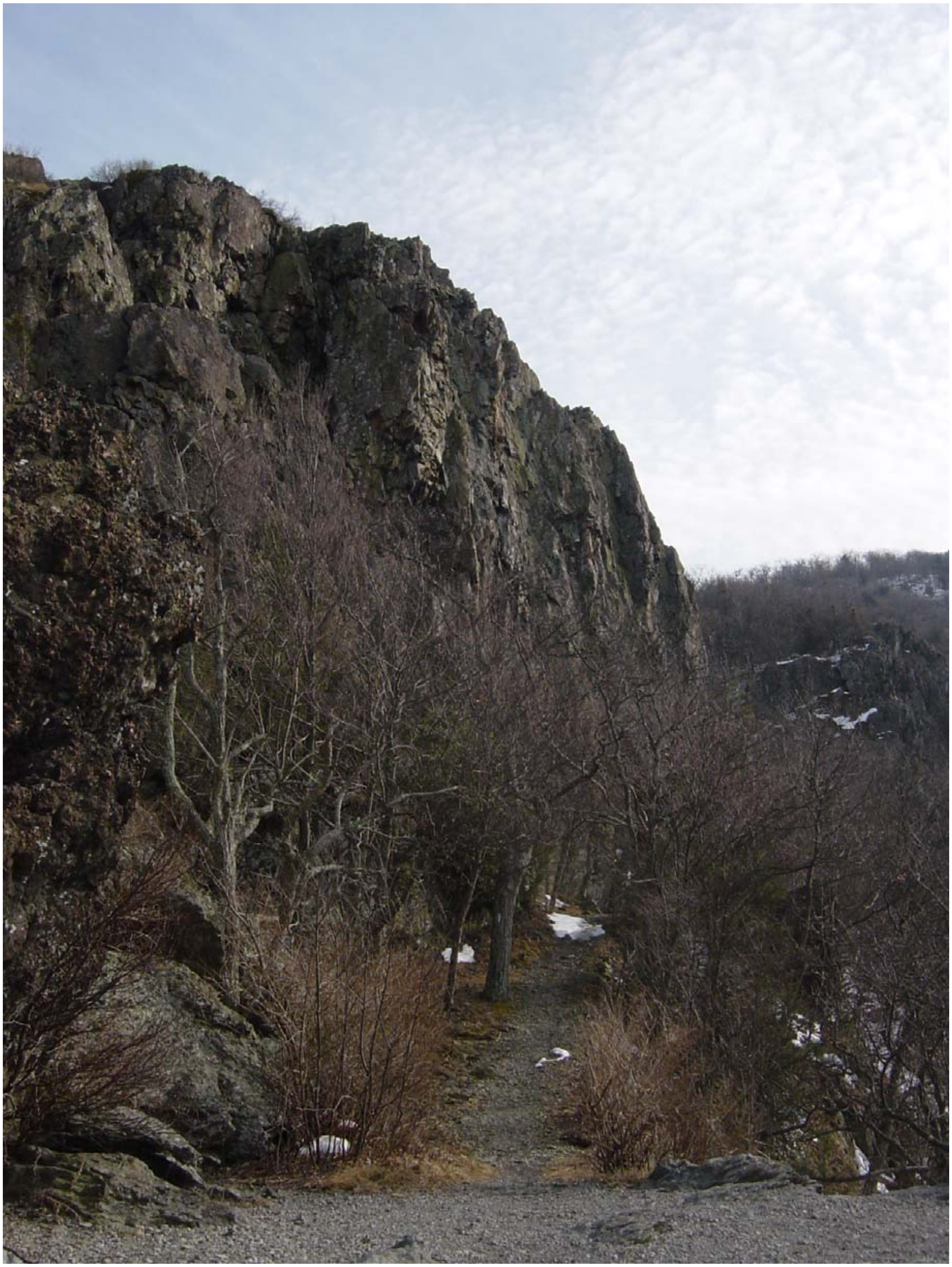

View of cliffs at Little Stony Man, Shenandoah National Park. Photograph by Trista L. Thornberry- Ehrlich (Colorado State University).

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Executive Summary

A Geologic Resources Evaluation scoping meeting took place at the Mimslyn Inn in Luray, VA, March 22- 23, 2005, including an afternoon field trip on March 22. The scoping meeting participants identified the following list of geologic resource management issues. These and more topics are discussed in detail on pages 15- 25.

1. Rock falls and debris flows, especially along Skyline Drive

2. Cliff management and research of the effects of visitor use on geologic features and threatened plant communities

3. Soil characterization and inventory as the missing link in an interdisciplinary approach to understanding the environment at Shenandoah

4. Periglacial geologic features including boulder fields and weathering processes active 15,000 years ago and today.

Introduction

The National Park Service held a Geologic Resource Evaluation scoping meeting for Shenandoah National Park near park headquarters of Luray, Virginia on Tuesday and Wednesday, March 22- 23, 2005. This meeting accompanied an afternoon field trip on March 22, 2005. The purpose of the meeting was to discuss the status of geologic mapping in the park, the associated bibliography, and the geologic issues in the park. The products to be derived from the scoping meeting are: (1) Digitized geologic maps covering the park; (2) An updated and verified bibliography; (3) Scoping summary (this report); and (4) A Geologic Resource Evaluation Report which brings together all of these products.

Shenandoah National Park was established during Franklin Delano Roosevelt's administration on December 26, 1935. Other designations include the Rapidan Camp as a National Historic Landmark, the Shenandoah Wilderness area (79,579 acres) on October 20, 1976, and the Skyline Drive as part of the National Register of Historic Places in 1996. Shenandoah covers 199,045 [2004] acres of Blue Ridge Mountains from Front Royal, VA to the southern entrance near Waynesboro, VA. It is one of the largest parks in the eastern United States. It protects some of the oldest rocks in the Appalachian Mountains and a variety of rare and threatened habitats.

Shenandoah National Park identified 45 quadrangles of interest. The U.S. Geological Survey, in a cooperative effort with the College of William & Mary, George Washington University, James Madison University, and others are creating a new, detailed geologic map for the park and its surrounding areas.

Other geologic maps covering portions of the quadrangles of interest and surrounding areas include:

- USGS I- 1313- C (1:125,000, 1983), I- 2607 (1:100,000, 2 sheets, 2000),
- USGS OF- 90- 548 (1:100,000, 1990), OF- 95- 629 (1:24,000, 1995), OF- 92- 716 (1:100,000, 1992), OF- 97- 708 (1:24,000, 1997), OF- 00- 263 (1:24,000, 2003), OF- 01- 188 (1:24,000, 2001), OF- 01- 227 (1:100,000, 2001)
- USGS Professional Paper (PP) 230 (1:31,250, plates 1 and 6, 1950)
- American Geological Institute 83- 108 (1:40,000, 1982)
- USGS MF- 2229 (1: 100,000, 1994), MF- 1527- A (1:48,000, 1985)
- Geological Society of America Special Paper 194 (1:208,000, 1984)
- Virginia Division of Mineral Resources (VDMR) Publications 143, 159 (1:100,000, 1996, 2001, respectively), Publication 15 (1:50,000, 1979), Publications 3, 4, 10, 11, 12, 13, 17, 60, 107 (1:24,000, 1977, 1978, 1978, 1978, 1978, 1978, 1980, 1986, 1991, respectively)

- VDMR Reports of Investigations 35, 40, 44, 45 (1:24,000, 1974, 1975, 1976, 1976, respectively), Report of Investigations 20 (1:62,500, 1969)
- VDMR Bulletins 76, 77, 78, 81, 86 (1:62500, 1960, 1962, 1963, 1967, 1976, respectively)
- West Virginia Geological Survey (WVGS) Country Geologic Report CGR- 8 (1:62,500, 1927)
- West Virginia Geological and Economic Survey (WVGES) Open File Report OF9201, (1:24,000, 1992)
- WVGES Map- WV 37 (1:24,000, 1992), Map 1 (1:250,000, 1968)
- WVGES Volumes V- 6a (1:250,000, 1986)
- Maryland Geological Survey (MGS) Geologic Map of Maryland (1:250,000, 1968)

This list is not exhaustive and many other maps exist that include coverage of the geology, oil and gas features, surficial geology, topography, groundwater features, land use, Landsat imagery, geochemical features, aeromagnetic- gravity, mineral and mineral potential, hazard features, stratigraphy, hydrogeology, structures, glacial features, karst features, etc. Additional mapping at a smaller scale will be more helpful for park resource management and interpretation. Features and units to include on future mapping include alluvium, colluvium, karst, debris flows, scars, talus and boulder fields, block fields, terraces, alluvial fans, dark mafic diabase dikes, and the ~ 20 delineated bedrock units now identified within the park.

Physiography

Shenandoah lies within the Blue Ridge physiographic province. In the area of Shenandoah the eastern United States is divided into 5 physiographic provinces. These are called the Atlantic Coastal Plain, Piedmont Plateau, Blue Ridge, Valley and Ridge, Appalachian Plateaus provinces. These are in turn subdivided into smaller subprovinces.

The Blue Ridge Province is located along the eastern edge of the Appalachian Mountains. It contains the highest elevations in the Appalachian Mountain system. These are in Great Smoky Mountains National Park in North Carolina and Tennessee. Precambrian and Paleozoic igneous, sedimentary, and metamorphic rocks were uplifted during several orogenic events to form the core of the mountain range. Today this comprises the steep, rugged terrain now exposed after millions of years of erosion.

Resistant Precambrian gneisses and granites, late Precambrian to early Cambrian greenstones, and Cambrian age quartzites form the heights of the Blue Ridge in Virginia (Nickelsen, 1956). The elongate belt of the Blue Ridge stretches from Georgia to Pennsylvania. Eroding streams have caused the narrowing of the northern section of the Blue Ridge Mountains into a thin band of steep ridges, climbing to heights of approximately 1,235 m (4050 ft). The Blue Ridge province is typified by steep terrain covered by thin, shallow soils, resulting in rapid runoff and low ground water recharge rates.

West of the Blue Ridge lies the Great Valley subprovince of the Valley and Ridge province. The eastern portion of the Ridge and Valley province is part of the Great Valley (Shenandoah Valley). Long, parallel ridges separated by valleys characterize the landscape of the Valley and Ridge physiographic province. These valleys were formed where resistant sandstone ridges border more easily eroded shale and carbonate formations, leaving valleys. This province contains strongly folded and faulted sedimentary rocks in western Maryland. It is connected to the Piedmont Plateau province by streams that cut through the Blue Ridge Mountains.

East of the Blue Ridge lies the Piedmont Plateau province. The eastward- sloping Piedmont Plateau was formed through a combination of folding, faulting, metamorphism, uplift and erosion. These processes resulted in a landscape of eastern gently rolling hills starting at 60 m (197 ft) in elevation that become gradually steeper moving westwards towards the western edge of the province at 300 m (984 ft) above sea level. The Piedmont Plateau is composed of hard, crystalline igneous and metamorphic rocks such as schists, phyllites, slates, gneisses, and gabbros. Soils in the Piedmont Plateau are highly weathered and generally well drained. The “Fall Line” or “Fall Zone” marks a transitional zone where the softer, less consolidated sedimentary rock of the Atlantic Coastal Plain province to the east, intersects the harder, more resilient metamorphic rock to the west, forming an area of ridges and waterfalls and rapids.

Geologic History of the Central Appalachian Mountains

The bedrock at the heights of the Blue Ridge Mountains in Shenandoah National Park is among the oldest in the eastern United States, dating back to the Proterozoic Era.

Proterozoic Era – In the mid Proterozoic, during the Grenville orogeny, a supercontinent formed which included most of the continental crust in existence at that time. This included the crust of North America and Africa. The sedimentation, deformation, plutonism (the intrusion of igneous rocks), and volcanism associated with this event are manifested in the metamorphic gneisses in the core of the modern Blue Ridge Mountains (Harris et al., 1997). These rocks were deposited over a period of a 100 million years and are more than a billion years old, making them among the oldest rocks known from this region. They form a basement upon which all other rocks of the Appalachians were deposited (Southworth et al., 2001).

The late Proterozoic, roughly 600 million years ago, brought a tensional, rifting tectonic setting to the area. The supercontinent broke up and a sea basin formed that eventually became the Iapetus Ocean. In this tensional environment, flood basalts and other igneous rocks such as diabase and rhyolite added to the North American continent. These igneous rocks were intruded through cracks in the granitic gneisses of the Blue Ridge core and extruded onto the land surface during the break- up of the continental land mass (Southworth et al., 2001). Today these flood basalts comprise the Catoctin Greenstone, a prominent geologic unit at Shenandoah. The Iapetus basin collected many of the sediments that would eventually form the Appalachian Mountains, including those of the Chilhowee Group in the Shenandoah area.

Early Paleozoic Era – During the Early Paleozoic, from Early Cambrian through Early Ordovician time orogenic activity along the eastern margin of the continent began again. The Taconic orogeny (~440- 420 Ma in the central Appalachians) was a volcanic arc – continent convergence. Oceanic crust and the volcanic arc from the Iapetus basin were thrust onto the eastern edge of the North American continent. The Taconic orogeny involved the closing of the ocean, subduction of oceanic crust, the creation of volcanic arcs and the uplift of continental crust (Means, 1995). Initial metamorphism of the Catoctin Formation into metabasalts and metarhyolites, as well as the Chilhowee Group Rocks into quartzites and phyllites occurred during this orogenic event.

In response to the overriding plate thrusting westward onto the continental margin of North America, the crust bowed downwards creating a deep basin that filled with mud and sand eroded from the highlands to the east (Harris et al., 1997). This so- called Appalachian basin was centered on what is now West Virginia. These infilling sediments are today represented by the shale of the Ordovician (450 Ma) Martinsburg Formation (Southworth et al., 2001).

During the Late Ordovician, the oceanic sediments of the shrinking Iapetus Ocean were thrust westward onto other deepwater sediments of the western Piedmont. Sandstones, shales, siltstones, quartzites, and limestones were then deposited in the shallow marine to deltaic environment of the Appalachian basin. These rocks, now metamorphosed, currently underlie the Valley and Ridge province to the west of Shenandoah National Park (Fisher, 1976).

This shallow marine to fluvial sedimentation continued for a period of about 200 My during the Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, and Permian Periods. This resulted in thick piles of sediments. The source of these sediments was from the highlands that were rising to the east during the Taconian orogeny (Ordovician), and the Acadian orogeny (Devonian).

The Acadian orogeny (~360 Ma) continued the mountain building of the Taconic orogeny as the African continent approached North America (Harris et al., 1997). Similar to the preceding Taconic orogeny, the Acadian event involved land mass collision, mountain building, and regional metamorphism (Means 1995). This event was focused further north than central Virginia.

Late Paleozoic Era – Following the Acadian orogenic event, the proto- Atlantic Iapetus Ocean was completely destroyed during the Late Paleozoic as the North American continent collided with the African continent. This formed the Appalachian mountain belt we see today and a supercontinent named Pangaea. This mountain building episode is called the Alleghanian orogeny (~325 – 265 Ma), the last major orogeny of the Appalachian evolution (Means, 1995). The deformation by folding and faulting produced the Sugarloaf Mountain anticlinorium and the Frederick Valley synclinorium in the western Piedmont, the Blue Ridge- South Mountain anticlinorium, and the numerous folds of the Valley and Ridge province (Southworth et al., 2001). Many of the faults and folds accommodating orogenic stresses are visible in Shenandoah National Park.

During this orogeny, rocks of the Great Valley, Blue Ridge, and Piedmont provinces were transported as a massive block (Blue Ridge – Piedmont thrust sheet) westward onto younger rocks of the Valley and Ridge along the North Mountain fault. The amount of compression was extreme. Estimates are of 20-50 percent shortening which translates into 125–350 km (75- 125 miles) of lateral translation (Harris et al., 1997).

Deformed rocks in the eastern Piedmont were also folded and faulted and existing thrust faults were reactivated as both strike slip and thrust faults during the Alleghanian orogenic events (Southworth et al., 2001). Paleoelevations of the Alleghenian Mountains are estimated at approximately 6,096 m (20,000 ft), analogous to the modern day Himalaya Range in Asia. These mountains have been beveled by erosion to elevations less than 1,235 m (4,051 ft at Hawksbill Mountain) in the Shenandoah area (Means, 1995).

Mesozoic Era – Following the Alleghenian orogeny, during the late Triassic, a period of rifting began as the deformed rocks of the joined continents began to break apart from about 230- 200 Ma. The supercontinent Pangaea was segmented into roughly the continents that persist today. This episode of rifting or crustal fracturing initiated the formation of the current Atlantic Ocean and caused many block- fault basins to develop with accompanying volcanism (Harris et al., 1997; Southworth et al., 2001).

Thick deposits of unconsolidated gravel, sand, and silt were shed from the eroded mountains. These were deposited at the base of the mountains as alluvial fans and spread eastward to be part of the Atlantic Coastal Plain (Duffy and Whittecar 1991; Whittecar and Duffy, 2000; Southworth et al., 2001). The amount of material inferred from the now- exposed metamorphic rocks is immense. Many of the rocks exposed at the surface must have been at least 20 km (~10 miles) below the surface prior to regional uplift and erosion. The erosion continues today with the Potomac, Rappahannock, Rapidan, and Shenandoah Rivers, stripping the Coastal Plain sediments, lowering the mountains, and depositing alluvial terraces of the rivers, creating the present landscape.

Cenozoic Era – Since the breakup of Pangaea and the uplift of the Appalachian Mountains, the North American plate has continued to drift toward the west. The isostatic adjustments that uplifted the continent after the Alleghenian orogeny continued at a subdued rate throughout the Cenozoic Period (Harris et al., 1997).

Though glaciers from the Pleistocene Ice Ages never reached the central Virginia area (the southern terminus was in northeastern Pennsylvania), the colder climates of the ice ages played a role in the formation of the landscape at Shenandoah National Park. Because of the proximity to the glacial environment as well as the high elevation, the mountains of Shenandoah experienced periglacial conditions that included discontinuous permafrost, tundra- like vegetation, and many freeze- thaw cycles per year. These freeze and thaw cycles led to the ice wedging of thousands of boulders and small rocks from the bedrock of the mountains. These stones slid down the slope as part of talus piles and larger, water- saturated masses slid over the partially frozen layer below in a process known as solifluction (Means, 1995).

Stratigraphy

The oldest rocks exposed along the mountain ranges of Shenandoah are commonly referred to as the Old Rag Granite, and the Pedlar Formation (Gathright, 1976). Modern U- Pb dating techniques and careful fieldwork have subdivided these units into greater detail than ever before (Dick Tollo, meeting communication 2005). The name Pedlar Formation is herein referring to a broad suite of granitic and gneissic rocks with a complex emplacement and deformational history. These Proterozoic age rocks are approximately 1.1 billion years old (Ga).

The Late Proterozoic Swift Run Formation is a discontinuous series of quartzites layered with phyllites and slates. This formation is present locally between the younger Catoctin Greenstones, and the older granitic gneisses. The Catoctin Greenstone is a relatively low- grade metamorphic remnant of a sequence of flood basalt flows, intrusive dikes, and pyroclastic ashes and tuffs up to 305 m (1,000 ft) thick at Shenandoah (Reed, 1969; Gathright 1976). The top surface of the greenstone is irregular indicating regional erosion between the time of its deposition and the deposition of the sands, shales, and conglomerates of the lower Chilhowee Group.

The Early Cambrian Chilhowee Group is exposed along the flanks of the mountains of Shenandoah. This group includes from oldest (lowest) to youngest (highest): the Loudoun Formation (phyllite with quartz pebble conglomerate), the Weverton Formation (quartzites and phyllites), the Hampton (Harpers) Formation (shales, slates, and phyllites with *Skolithos* worm borrow trace fossils), and the Erwin (Antietam) Formation (quartzite with trilobite fossils elsewhere) (Harris et al., 1997; Southworth, meeting communication 2005).

Intense erosion following the uplift of the mountains is responsible for the landscape at Shenandoah, thus the units deposited during the later Paleozoic, Mesozoic, and most of the Cenozoic Eras are not present in the park. Several diabase dikes swarms intruded during the Triassic- Jurassic extensional tectonic regime. These are exposed in the southern and central sections of the park.

Flanking the slopes and lining the many stream and river valleys of the park are colluvium, alluvium, and other slope deposits, and periglacial talus deposits including boulder fields,. Debris flows following heavy rains move massive slumps of material down the steep mountain slopes. Along the western flanks of the park, several alluvial fan deposits spread into the valley below.

Structure

The Blue Ridge Mountains expose the roots of an ancient mountain chain. The rocks exposed at the height of the Blue Ridge (~1,006 m, 3,300 ft) are buried ~3,658 m (~12,000 ft) below the surface in the Shenandoah Valley west of the park.. Because of this, Shenandoah National Park offers unique opportunities to look at the infrastructure of a fold and thrust belt, a view into the earth's crust.

The allochthonous Blue Ridge reaches its northern terminus in southern Pennsylvania. At this northern end, the Blue Ridge consists of a northeast-plunging, asymmetric anticlinorium, locally referred to as the South Mountain (Blue Ridge) anticlinorium (trending N20°E) (Logan and Dyer, 1996). Shenandoah National Park sits on the western limb of the Blue Ridge anticlinorium structure. It extends southwestward nearly 400 km (249 miles) to the Roanoke, Virginia area (Mitra, 1989). The anticlinorium marks the easternmost extent of the Blue Ridge Province in Virginia

The entire structure is locally overturned to the northwest. The west limb dips steeply southeast, the crest is broad and flat and the east limb dips approximately 50 degrees southeast. The anticlinorium exposes Grenville age granodiorite and granitic gneiss in its core and is flanked on each side by Precambrian and Lower Paleozoic metasedimentary and metavolcanic rocks (Mitra, 1989).

The Swift Run (phyllites and quartzites), Fauqier and Mechum River (metamorphosed clastic sedimentary rocks), and Catoctin (greenstone, metarhyolite, and metasediments) Formations unconformably overlie the Precambrian gneissic rocks in the northern Virginia area. The structural style of the anticlinorium is continuous across the Great Valley and into the Valley and Ridge Province. The anticlinorium is associated with Alleghenian thrusting above a detachment that extends eastward into the Piedmont Plateau Province (Onasch, 1986).

Structures along the limbs of the anticlinorium suggest multiple phases (as many as four) of folding and at least one metamorphic event. The anticlinorium was formed during the Alleghenian orogenic event in the Late Paleozoic, however, several phases of folding predate the greenschist (low- grade) metamorphism associated with the orogeny and therefore may represent prior Taconian or Acadian orogenic deformation (Onasch, 1986).

The folding and thrusting of the Blue Ridge rocks was accompanied by a strong cleavage, or parting, in the rocks. This cleavage and associated fractures strike northeast and dip ~ 45 degrees southeast, indicating different orientations of movement and deformation within the structure (Trombley and Zynjuk, 1985).

Asymmetric folds are visible in Chilhowee Group outcrops, predominantly in the southern sections of the park (Harris et al., 1997).

Faults within Shenandoah have had a pronounced influence on landform development. Several large low- to high- angle thrust faults dipping to the southeast are present along the length of the park, many as brecciated zones, though most traces are covered with slope talus and other debris. These thrust faults moved the Blue Ridge rock mass atop the younger Paleozoic Chilhowee Group rocks to the west (Harris et al., 1997). Thrust faults include the Front Royal fault that thrusts Chilhowee Group rocks onto younger limestones west of the park, and other roughly parallel thrust faults running the length of the park (Southworth, meeting communication 2005). Crosscutting, steeply inclined strike- slip faults, trending northwestward across the Blue Ridge are responsible for the uneven summits and irregular lobe and embayment pattern to the rock distribution along the eastern edge of the park (Harris et al., 1997).

Significant Geologic Resource Management Issues in Shenandoah National Park

1. Rock falls and debris flows

Rockfalls along trails, roads, and Skyline Drive are one of the most serious geologic hazards in the park. Rockfalls are often triggered by seismic events. The largest regional seismic event to be measured by the Central Virginia seismic center is a magnitude 4.5. However, seismic risk at the park is relatively low and most rockfalls are likely due to undercutting and frost action wedging the rocks apart on a slope.

In 2003, a rockfall closed Skyline Drive and required blasting to clear the road. Mary's Rock tunnel has seasonal icing problems that are wedging the blocks of rock apart. The seasonal ice closes the road, but the potential for greater hazards due to rockfall are present. Visitor safety is also a resource management concern along the cliffs, rock outcrops, and steep slopes at Shenandoah. The many waterfalls in the park are scene to several slipping accidents each year. The interesting geology at the park causes concentrations of visitor interest in areas such as Little Stony Man and Old Rag Mountain. This increase in visitation also has an impact on the resources and should be focused on for visitor safety evaluation.

In 1995, a sever microburst sent inches of rain falling in a relatively small area of Shenandoah National Park. The resulting debris flows damaged property and exposed bedrock geology for study. Debris flows are a critical resource management concern. These natural phenomena are threatening backcountry camps, and properties beyond park boundaries. However, debris flows are primarily activated by storms, are difficult to predict, and it is difficult to determine vulnerability versus the geographical distribution of the flows. Rainfall threshold curves determine when warnings should be sent out to residents living at the bases of Shenandoah's slopes.

Research and monitoring questions and suggestions include:

- Map and inventory debris flow locations.
- Encourage surficial mapping that locates debris flow deposition sites.
- Should current flows be monitored?
- What is the recurrence interval for debris flows along a given path?
- Look at recently failed debris flow locations and focus on nearby areas more apt to fail during a storm event.

- Cooperate with the weather services to look at storm and rain surge patterns to aid in prediction of debris flow events; encourage increases in county coverage to get warnings posted.
- Inventory fracture geometries and determine risk for rockfall using kinematic models that predict which fracture sets are likely to fail in a given outcrop.
- Perform a systematic survey of all roadcuts along Skyline Drive.
- Inventory soil types, focusing on areas where soil sloughing is occurring such as the east side of Thornton Gap.
- How should slopes along Skyline Drive be stabilized?
- Inventory sensitive features such as cave openings and rare plant communities to protect them from public use.

2. Cliff management

The cliffs at Shenandoah are comprised of granitic gneisses, greenstones, and metasedimentary rocks. These features are responsible for many of the scenic vistas at the park, the waterfalls, and numerous recreational opportunities including climbing. They are also host to several rare and unique biologic communities and vulnerable to degradation with overuse. A cooperative research effort is underway to understand the nature of the cliffs at the park and their role in the park's ecosystem in an attempt to effectively manage this vital resource.

Research and monitoring questions and suggestions include:

- Map cliffs to assess plants, animals, and rock types.
- Create a Cliff Management Plan that balances ecosystem integrity with visitor use and responsible resource management.
- Establish geologic criteria of cliffs to understand hiking and other use patterns.
- Capture linear shapes of cliff outcrops, compare with a baseline outcrop (one with no identifiable human impact).
- Should some areas be designated "sacrificial" cliffs to concentrate impacts?
- Quantify extent to which human impacts are destroying unique biologic communities as well as geologic features at cliff sites.
- Use Terrestrial 3- D laser scanning to survey cliffs

3. Soil characterization and inventory

Soils and geology are very closely related. The soil type is directly correlative with the underlying geologic units from which the soil formed. Soil surveys are more complicated because of external influences such as wind blown contributions, water transported materials, and vegetation. Because soils in effect act as an interface between the biota and the geology, their characterization is vital in understanding how to manage the entire ecosystem.

As more geologic research occurs at Shenandoah, the story is getting more complicated. Refinements in the geologic understanding at the park have profound effects on any soil studies. Geology should be emphasized during soil research and inventories.

Research and monitoring questions and suggestions include:

- Perform a soil survey.
- Emphasize the relationship between geology and soils in resource management decision making and interpretive programs.
- Determine extent to which soils are being degraded at visitor hotspots including vistas, hiking trails, campgrounds, and climbing areas.
- Send a geologist with soil scientists to incorporate the connections between geology and soil science.
- Is the soil at Big Meadow glacial loess?

4. Periglacial geologic features

Several outcrops of folded and faulted metamorphic rocks are scattered throughout the park. When exposed to weathering on a slope, the wedging action of water in cracks, joints and fractures breaks the rock down in a unique way resulting in distinct columns of rock standing isolated from the neighboring slope. During the colder months, melt water from snow trickles through cracks in the rock and freezes at night, wedging the rocks apart.

Ice wedging was especially active during the periglacial conditions of the Pleistocene Epoch. Thousands of boulders and smaller rocks litter the bases of rock outcrops as talus. When caught up in a water- saturated mass, they slide down the slopes along frozen layers of ground in a process known as solifluction (Means, 1995). The slopes of at Shenandoah are littered with these stony remnants.

There are three basic types of periglacial landforms present at Shenandoah: boulder- covered slopes, side- slope stone "streams", and step features that act as sources of sediment for debris flows. Boulder- covered slopes are classified as areas covered by boulders that are up to 6 m (20 ft) long and are spaced less than 15 m (50 ft) apart. Side- slope stone streams are linear deposits of smaller boulders averaging 1 m (3 ft) in length and are spaced less than 0.6 m (2 ft) apart.

These periglacial features at Shenandoah have yet to be comprehensively inventoried, characterized, and mapped. Identifying these features is tricky since many stream bottoms are littered with large stones. The angular nature (typical of frost wedging) and size of the boulders differentiates them from typical alluvial boulders that tend to be smoother and rounded.

Research and monitoring questions and suggestions include:

- Study, inventory, characterize, and map the periglacial features present at Shenandoah including boulder fields, stone streams, and periglacial step features.
- Why are periglacial features best exposed over quartzites, greenstones, and granites?
- What is the rock type distribution for the periglacial boulders?
- Relate periglacial features and weathering processes with the active landscape at Shenandoah for interpretive presentations; possibly focus on the weathering at Old Rag Mountain.

5. Global climate change

From rising sea level to regional droughts, climate change is a global concern. At Shenandoah National Park, large catastrophic storms occur once ever 2,000 - 3,000 years. For the Appalachians as a whole, that recurrence interval is just once every three years. These storms are not inclusive of the cloudbursts and tropical storms that occur nearly every season in the park. These storms are responsible for slope erosion, debris flows, and increased sediment load into the watersheds beginning in the park. This leads to property damage downslope and undermines building foundations, roads, trails, and other visitor use facilities within the park as well.

At Shenandoah National Park, climate change also has a drastic effect on the rare plant communities that exist on the highest peaks. These communities are in decline due to global warming and human impacts. Meteorologic and microclimatic data are patchy for the park, though independent studies of the acid rain inputs and paleoclimate through the University of Virginia and others adds to the overall knowledge of the effects of climate on the park's resources.

Research and monitoring questions and suggestions include:

- Compile all existing meteorologic and microclimatic data for the park and store in a database for resource management use.
- Encourage further cooperative efforts with local universities, government agencies, and other groups to study the climate at Shenandoah and the effects of change.
- Perform acid rain measurements and correlate with the underlying bedrock to determine if any buffering effects occur. Relate this information to the water quality for the park.

- Perform clay mineralogy and grain size studies on the soils in the park, relating these to pollen studies to determine paleoclimatic patterns.
- Are there other environments, perhaps further north, that may be suitable for migration of rare plant communities in the interest of preserving rare and threatened species?

6. Surface water and sediment loading

Shenandoah is the source for many watersheds in the surrounding central Appalachian area of Virginia. As such, the quality of the surface water at the park is very important to surrounding communities. Soil compaction due to increased visitor use as well as impervious surfaces is increasing seasonal runoff as sheet flow. Many of these areas are managed by engineering solutions such as culverts, bridges, etc.; however, the pervasive vegetation at the park tends to hide these features, making the management of them difficult.

Flooding and channel erosion naturally occur along most of the streams and rivers within the park. At Big Meadows, flooding and erosion are threatening the wetlands and visitor facilities, including the campgrounds in the area. Water contamination levels due to pit toilets, improper septic systems, and wastewater treatment areas are largely unmonitored. Administration at the park is currently in the process of resolving some of the contamination issues.

Alterations to park vegetation along the steep, exposed slopes lead to changes in the hydrologic regime at the park. For example, loss of hemlock trees and their stabilizing roots due to the gypsy moth, is leading to increased sediment load in nearby streams and could potentially contribute to debris flows. In addition, administrative roads are not being properly maintained along the slopes at the park. Grading and bulldozing of these roads can cause high sediment loading of crossing streams. Horse trails, hiking trails and other high use areas are also at risk of intense erosion leading to sediment loading.

Research and monitoring questions and suggestions include:
- Study and map all wetlands existing within the park.
- Measure surface water freeze and thaw cycles, determining key points for monitoring.
- Research stream sediment loads to determine their effects on aquatic and riparian biota. Is sediment loading in the park streams following a seasonal pattern? Meadow Run could be a focus area.
- Study the denudation of streams in upland areas.
- Is drainage from abandoned mines changing the pH of surface water in the park and/or adding contaminants such as mercury?

- Accurately map park administrative roads and target streams and areas of erosion for remediation.
- Determine any hotspots for water contamination; remediate and monitor results.
- Determine effects, if any local karst features have on the watersheds at Shenandoah.

7. Groundwater

Approximately 20 acres of the park are in karst- affected areas. A cave on the northwest side of the park is known to be a "bad air" cave. This cave has dangerous CO_2 levels that pose a threat to explorers. This and other caves need to be comprehensively inventoried to manage visitor safety.

Springs and wells are the primary drinking water supply source for the park. According to groundwater studies conducted at Big Meadows, the groundwater at the park is very young. There are many wells throughout the park that could be used for park wide monitoring of ground water quality. There are six wells in Big Meadows alone. The hydrogeologic system is fracture driven and the park is a large recharge area for the surrounding valleys' aquifers.

Research and monitoring questions and suggestions include:

- Inventory groundwater levels at Big Meadows.
- Map and characterize all karst features within the park.
- Perform a comprehensive cave inventory at the park.
- Perform dye tests to look at the hydrogeologic effects of karst on the watersheds at Shenandoah. Previous focus areas included Dickey Ridge Trail.
- Test for and monitor phosphate and volatile hydrocarbon levels in the groundwater at the park, focusing on areas near facilities.
- Are CFC levels elevated in the groundwater at Shenandoah?
- Test water quality at springs in the park.
- Monitor groundwater quality near Lewis Springs, focusing on the potential contamination by a 4,000- gallon diesel tank there.
- Create hydrogeologic models for the park to better manage the groundwater resource and predict the system's response to contamination.
- Perform lithogeochemical mapping to determine the buffering potential of the bedrock, the interaction between acidic meteoric water and the underlying geology, and the ecosystem's response to changes in water chemistry.

8. Recreational use and interpretative services

Interpreters make the landscape come alive for visitors and give the scenery a deeper meaning. Because geology forms the basis of the entire ecosystem and is directly responsible for the unique history at Shenandoah, geologic features and processes should be emphasized to improve the visitor's experience. Due to budget problems, many of the signs and exhibits at the park are outdated or are blatantly wrong. The website for the park needs to be updated for geologic content and connections with other scientific and cultural disciplines.

Research and monitoring questions and suggestions include:

- Replace inaccurate or outdated signage.
- Encourage the interaction between geologists and the interpretive staff to come up with a list of features to characterize and programs to implement
- Create a general interest map with simple explanatory text for visitors to the park.
- Update the park website relating geology with other resources.

9. Wind erosion of soils

Changes in vegetation along the highest peaks in the park are leading to changes in soil distribution as well. When vegetation dies off and winds pick up, soil is eroded away. Rare plant and lichen communities are retreating from the higher elevations making soil erosion an increasing management concern.

Research and monitoring questions and suggestions include:

- Inventory soil types at Shenandoah.
- Monitor rate of soil loss throughout the park focusing on devegetated areas and high use areas.

10. Fossil resources and unique geologic features

Within the Hampton (Harpers) Formation of the Chilhowee Group, some of the earliest forms of life left trace fossils. *Skolithos,* a worm, left burrows in this formation. These features are rather unique, as vertical burrows in quartzite. They are from the Early Cambrian era, ~500 Ma. In Adams City, PA, trilobite fossils were found in the Erwin (Antietam) Formation. These first fossils date the base of the Cambrian there at 545 Ma. Trilobites have yet to be found in Shenandoah.

Settings for type sections exist throughout Shenandoah National Park. There is a type section for the Swift Run Formation along U.S. Highway 33 at Swift Run Gap. The exposures of the Old Rag Granite lend themselves to type section possibilities. Other units are examples of "outstanding field examples" on many regional geologic maps. Research on the Precambrian Blue Ridge geology is shedding new light on the ancient history of the area. Samples and rocks from Shenandoah are making this research possible. Though many samples are destroyed upon analysis, those that are not should be identified and shared to the best extent available.

Many of the rare and interesting rocks and minerals at Shenandoah are attractive to collectors who are illegally removing samples from the park. These rare rock types include unekite, hydrothermally weathered granite with epidote and blue quartz, large crystals in the Old Rag Granite, magnetite, copper minerals within the greenstones, dramatic red jasper in the greenstones, and *Skolithus* burrows.

Given the bounty of unique and interesting rocks at Shenandoah, a collection should be available and catalogued at the park. A scope of collection document for the park would help define boundaries regarding which specimens the park can accept from outside donors. A scope of collection document would also help determine which specimens do not belong in the park's collection.

Research and monitoring questions and suggestions include:

- Should dating samples be shared with the public?
- Should outcrops be cleared of vegetation for educational purposes?
- Are trilobite fossils present in the Erwin Formation in the Shenandoah area?
- Attempt to locate and acquire fossil and rock samples previously taken from the park.
- Is the contact between the Catoctin Formation and the Chilhowee conformable? Are there any layers between these two units?
- What age are the lowest Chilhowee beds in the park?
- Search for a datable (volcanic) unit in the Chilhowee Group at Shenandoah.
- Date tuffaceous units within the Catoctin Greenstone.
- Encourage agreement in scientific language and mapping lexicons.
- Prepare a document detailing the scope of collection for Shenandoah National Park.
- Why is so much rock exposed at Old Rag Mountain? What are the causes of this exposure?
- What causes features such as Big Meadows to persist at altitude?

11. Disturbed lands

Abandoned mines, quarries, and assay pits dot the landscape at Shenandoah. The state of Virginia has an inventory of mine features such as small copper mines, and manganese mines. In the south district of the park, near the entrance station is a small quarry excavated for building stones during the 1930's. Along the western side of the south district, atop fan deposits are a series of ponds. These features are most likely manganese prospects and exploration pits opened during

World War II when mining was proposed. During World War I, prospectors excavated shafts, tunnels, dumps and pits in a search for iron ore. Madison Run Furnace was an iron smelter located on a restricted fire road. There was extensive mining of copper at Skyland and Dark Hollow between 1848 and 1911. These historical features could be targets for an interpretive program.

These features pose several concerns for resource management. Visitor safety is a constant concern wherever open shafts and loose tailings are associated with a mine feature. Most mine features, accessible to the public have been blocked or filled. Stability of tailings has not been determined. Another resource management concern is the collecting of rare and unique mineral samples from the abandoned mine features. For example, on top of Stony Man, theft of azurite and malachite (copper ore minerals) has occurred.

Research and monitoring questions and suggestions include:

- Consult the Virginia Department of Mineral Resources database for abandoned mine information.
- Perform a stability survey, focusing on mine tailings within public zones.
- Promote more interpretive programs on the historical search and extraction of useful geologic resources from Shenandoah.

11. Human Impacts

Humans began settling the slopes of the Blue Ridge and the Shenandoah Valley in the 1700's. Their farming and homestead activities created an unnatural landscape that persists today at Shenandoah National Park. Minor irrigation features, removal of soil and rocks, stone fences, grazed pastures, extensive logging, and other homestead features dot the landscape especially in the western edge fans and stream hollows.

Human impacts continue today as gas pipelines, cellular towers, microwave towers, power lines, roads, buildings, trails, visitor use areas, unnatural forest fires, imported (invasive) species, acid rain, and air and water pollution take their toll on the landscape. Resource management of these impacts is an ongoing process. Skyline Drive experiences constant stability problems as features designed in the 1930's are no longer adequate. These problems include rotting timbers, inadequate and improper fill, inadequate culverts, and bulging rock walls and retaining walls.

Fires are an important part of forest ecosystem renewal. However, manmade fires such as the Fultz Run Fire and the Stone Top Fire are directly related to urban encroachment on the Shenandoah area. Previous fire management strategies have increased the understory vegetation, leading to hotter, more devastating fires. Fires are typically small in scale, but removal of vegetation on the steep slopes at Shenandoah can have long lasting effects.

Research and monitoring questions and suggestions include:

- Are unnatural landscapes contributing to sinkholes and debris flows?
- Should the unnatural landscapes created by early settlers be remediated, or should the park continue to allow natural succession and disturbance run their course on these areas?
- Are fires and debris flows related?
- Research effects of fires on soil erosion and debris flows.
- Determine natural fire recurrence interval and map zones of fire severity.
- Plot areas of dead trees to focus future erosion control measures.
- Are soils becoming more acidic due to acid rain?
- Monitor chemical alterations in bedrock.
- Monitor chemical flow in groundwater and soils.
- Map culverts and other flow concentration features along fire and other administrative roads.
- Prepare a remediation plan for Skyline Drive, which as a cultural landscape should preserve historic structures and features in a manner that is safe to visitors.

12. Geologic – biologic relationships

Biology and geology are closely related in any ecosystem. Geology forms the foundation for soils and biota. The relationships between geology and biology at Shenandoah are poorly understood and yet powerful correlations exist between unique and rare species and the underlying geology. For example, a particular species of salamander prefers greenstone talus deposits for its habitat. Similarly, there are rare lichen and plant communities along the highest peaks of the Blue Ridge at Shenandoah. This is a direct correlation with the geologic structure of the area. Other unique environments at the park include high elevation greenstone barrens, talus fields, cliffs, high elevation residual forests, and shale barrens (shale barren phlox).

Given the geologic research interest and Shenandoah and the vast biologic knowledge of the park, a unique opportunity exists to promote an interdisciplinary approach to scientific study at the park. A comprehensive soil survey is a fundamental missing link between the geology and biology at Shenandoah. The Blue Ridge Mountains are oriented perpendicular to weather direction making it a rather special laboratory to research the effects of human industrial activities as well.

Research and monitoring questions and suggestions include:

- Map greenstone talus deposits and monitor for salamanders.
- Incorporating biologic inventories, soil studies, and refined geologic studies (geologic units and structures), determine direct relationships to manage and monitor.
- Create an interpretive program highlighting the interconnectivity between the landscape including the biota and the geology beneath it.
- Determine areas at highest risk of degradation and attempt to reduce visitor impact.

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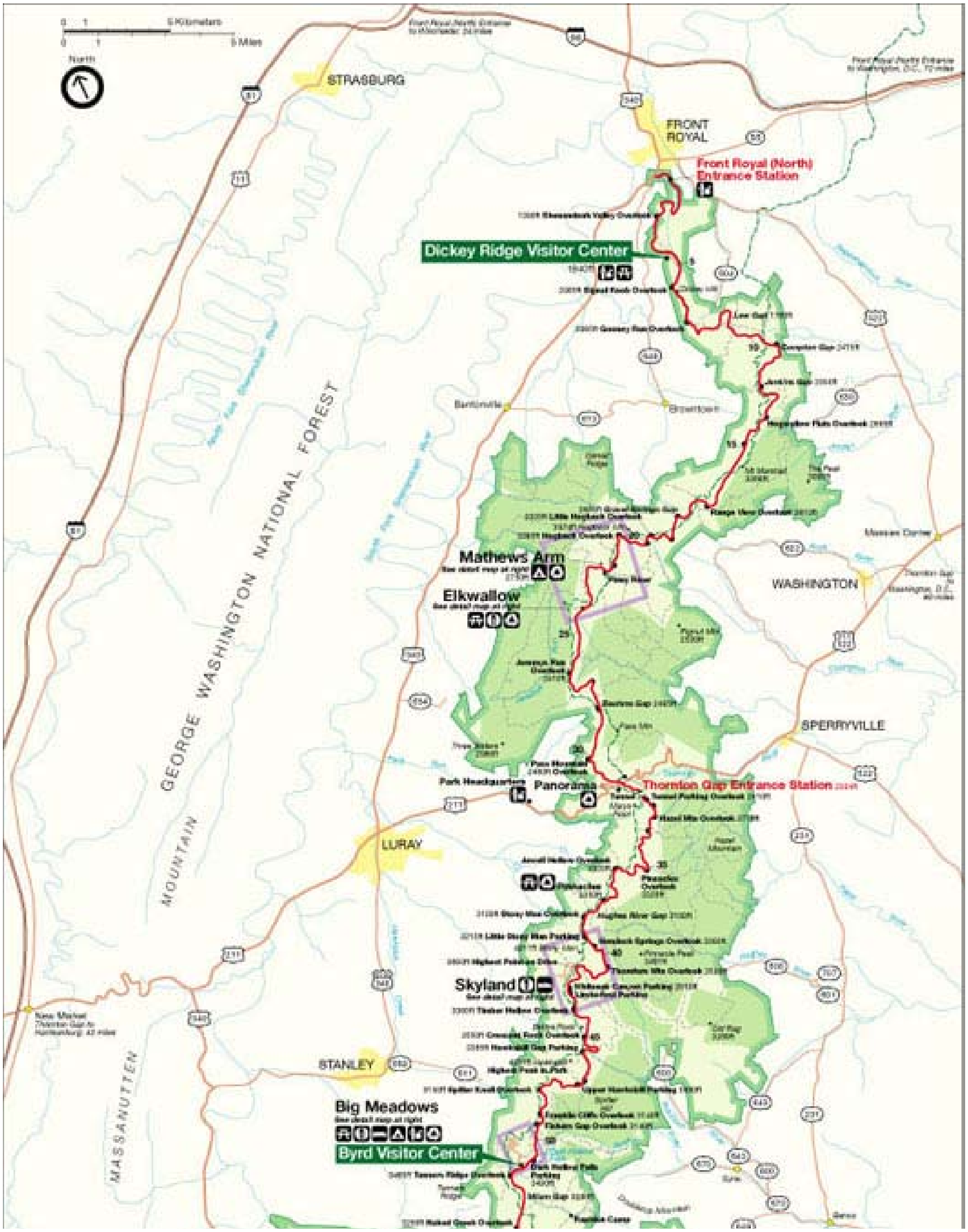
Map of Shenandoah National Park

Northern Section



Southern Section